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HYDROKINETIC TURBINE MODELS IN COMPLEX CHANNEL TOPOGRAPHY: LOCAL SCOUR, SEDIMENT TRANSPORT AND DEVICE PERFORMANCE.

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ABSTRACT

Accelerating marine energy development requires investigating the interactions between the engineered environment and its surrounding physical and biological environment. The complex and energetic physical environments desired for such energy conversion installations provide difficulties for efficient and sustainable device designs. One area of investigation focuses on the interactions between the channel topography and substrate material and its impacts on the structural integrity of hydrokinetic devices, as well as device impacts on local scour and far-field sediment transport. Laboratory experiments on such interactions performed at St. Anthony Falls Laboratory, University of Minnesota, USA provide an indication of how small-scale hydrokinetic devices can inform device developers and provide robust data for computational model validation to address the interactions between energy conversion devices and the physical environment. Model axial-flow current-driven 3-bladed turbines (rotor diameters, d_T = 0.15m and 0.5m) were installed in open channel flumes with both erodible and non-erodible substrates. Device induced local scour was monitored over several hydraulic conditions and material sizes. Additionally, synchronous velocity, bed elevation and turbine performance measurements provide an indication into how channel topography influences device performance. For comparison, a complimentary set of experiments was performed in a realistic meandering outdoor research channel with active sediment transport to investigate device performance in asymmetric channel flow environments. The suite of experiments in rectangular and meandering channels with stationary and mobile substrates provides an in-depth investigation into how axial-flow hydrokinetic devices respond to channel complexity, and how they impact local and far-field sediment transport characteristics. Results will be discussed in context with addressing uncertainties surrounding physical environment impacts of current-driven turbines and methods for informing future device development and advanced control strategies.

Keywords: Marine hydrokinetic energy, sediment transport, turbine performance characterization

1. INTRODUCTION

Few studies have investigated interactions between marine hydrokinetic (MHK) devices and the morphodynamic environment (Neill et al. 2009; Neill et al. 2012; Chen and Lam 2014; Hill et al. 2014; Robins et al. 2014; Hill et al. 2015), despite being identified as an area of uncertainty and concern regarding environmental impacts of this burgeoning industry (Cada et al. 2007; Foufoula-Georgiou et al. 2011; Shields et al. 2011). Facilities at St. Anthony Falls Laboratory (SAFL) at the University of Minnesota (UMN), USA, have provided an excellent platform for experimentally investigating MHK interactions with the physical environment while providing robust datasets for computational fluid dynamics (CFD) model validation. Despite the key insights gained from these preliminary investigations, there remains a large parameter space yet to be explored. Recent computational advances modeling complex natural turbulent flows (Kang et al. 2011) and hydrokinetic turbine wakes (Kang et al. 2014), especially in environments with active sediment transport or scour around hydraulic structures (Khosronejad et al. 2011, Khosronejad et al. 2012), provide a great opportunity to couple experimental and computational models to address uncertainties regarding the interactions between full-scale turbine(s) and the physical and ecological environment, a critical task for advancing the MHK industry.

As shown in Chamorro et al. (2013), hydrokinetic turbine performance is directly correlated to the scales of turbulent eddies present in the approaching flow environment. Not only is turbine power output modulated by the large scale coherent motions, but wake stability and mean velocity recovery are also dependent on the size of coherent eddies and turbine proximity to the eddy generating obstacle (Chamorro et al. 2015). As turbines are expected to be deployed in arbitrarily complex terrain, it is critical to develop an understanding of their response to both stationary and mobile topographic features. The characterization of these features, along with turbulent flow characteristics, are essential for developing site specific turbine locations to optimize individual turbine and total turbine array power output.

Multi-scale experiments at SAFL have begun demonstrating the interactions of MHK devices and the morphodynamic environment. Single turbine large-scale experiments and both single and multi-turbine array investigations completed at small-scale have provided key insights on how both stationary and mobile topography impacts device performance, and how turbines interact with erodible channels under both clear water and live bed sediment transport regimes. The experimental facilities at SAFL are briefly described in Section 2. In Section 3, results highlight the turbine response to complex channel bathymetry and turbine-induced impacts on near and far-field sediment transport. Future implications and applications towards advanced controls are discussed in Section 4, followed by concluding remarks in Section 5.

2. EXPERIMENTAL FACILITIES

The experiments presented herein were completed at SAFL at the UMN. Uniquely positioned on the Mississippi River with multiple scales and capabilities of facilities combined with state-of-the-art data acquisition capabilities, SAFL provides a test bed for investigating the interactions between hydrokinetic turbines and the hydrodynamic and morphodynamic environments. A series of small-scale and large-scale hydrokinetic turbine experiments utilized three different facilities to investigate turbine response in a variety of turbulent open-channel flow environments within channels containing rigid, erodible or mobile substrate material.

Large-scale turbine experiments (rotor diameter, d_T = 0.5m) were completed in the SAFL main channel (2.75m wide, 1.8m deep and 85m long) (Fig. 1, left). Investigations used a 1:10 scale 3-bladed axial flow turbine model mounted above both non-erodible and erodible sand channel material. The turbine angular velocity was precisely controlled with a stepper motor (Chamorro et al. 2013). Synchronous measurements of rotor torque and inflow velocity provided performance characterization and turbine response to coherent eddies introduced by stationary obstacles (Chamorro et al. 2015) and mobile topography. Spatial-temporal measurements of bed elevation, $z_b = z(x,y,t)$, were obtained using a state-of-the-art data acquisition (DAQ) system designed at SAFL. These measurements provide mm-scale 3D resolution of the spatial and temporal evolution of local scour (Hill et al. 2014) and passage of bedforms past the turbine location.

Small-scale experiments were completed in two different facilities. The SAFL Tilting Bed Flume, a rectangular straight channel (0.9m wide, 15m long and 0.6m deep) with slope adjustment capabilities, was first used to study relationships between channel roughness size and location with the corresponding turbine performance (Fig. 1, center). Turbine(s) (rotor diameter, d_T = 0.15m), were outfitted with miniature DC motors to monitor turbine performance. Additionally, turbine influence on local scour and far-field sediment transport characteristics was monitored continuously during experiments with several configurations of aligned and staggered turbine arrays.

Finally, the SAFL Outdoor StreamLab (OSL) provided a unique opportunity to investigate the effects of helical flow patterns and asymmetric channel geometry with active sediment transport on the performance, wake characteristics, and turbine influence on channel topography in a laboratory setting (Fig. 1, right). The OSL is a 40m by 20m experimental area with a sand-bed meandering stream (average width b = 2.7m, average depth h = 0.3m, sinuosity 1.3). The system is fed by Mississippi River water under valve control, thereby allowing precise control and monitoring of flow rates through the system (Khosronejad et al. 2014). The bed sediment is mobile fine-to-medium-grained sand (d_{50} = 0.75mm). The same small-scale turbine (d_T = 0.15m) was placed in the apex of the middle meander bend. Inflow velocities, turbine voltage output, and spatio-temporal bed elevations were monitored to study the interactions between the turbine and the meandering channel.

Figure 1: (Left): The SAFL Main Channel showing 0.5m diameter turbine. (Center): SAFL Tilting Bed Flume with 7 turbine staggered array during small-scale turbine experiments. (Right): Photograph of the SAFL Outdoor StreamLab (OSL) meandering stream.

3. RESULTS

3.1 Channel bathymetry influence on turbine performance

Channel roughness size and upstream location impacted turbine voltage output (i.e. performance) during the small-scale experiments. Fig. 2 highlights the correlation between mean turbine voltage output and the location of channel roughness features from experiments with either large-scale dunes (red line) or small-scale roughness (black line). The larger roughness features (dunes) have a stronger correlation to the turbine performance, especially when located approximately 1dT upstream of the rotor. As demonstrated in Chamorro et al. (2015) using a stationary cylindrical pier, these mobile roughness features can be considered quasi-stationary in time. Similar to coherent eddies shed by permanent hydraulic structures, ripples and dunes introduce turbulent coherent eddies into the flow on their downstream side which impacts turbine performance.

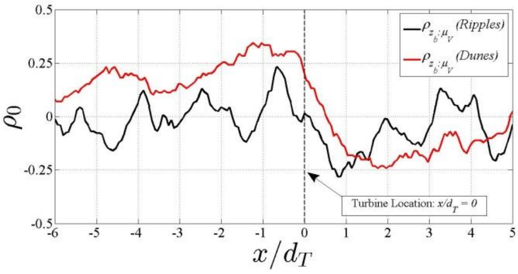

Figure 2: Correlation between bed elevation and mean turbine voltage (i.e. performance) from small-scale experiments with dunes (red line) and ripples (black line). Results provide indications of bathymetry length scale importance for future advanced control strategies.

3.2 Turbine influence on sediment transport

Large-scale experiments with the turbine operating above an erodible channel with no active bedload transport show an increase in local bed shear stress and local scour development immediately downstream of the rotor location (Fig. 3 modified from Hill et al. 2014). Maximum scour depths reached approximately 25% of the rotor diameter and extended 1d_T in the streamwise direction. Ongoing analysis is investigating the spatial and temporal evolution of local scour and bedform geometric characteristics during active sand bedload transport with ripples and dunes present.

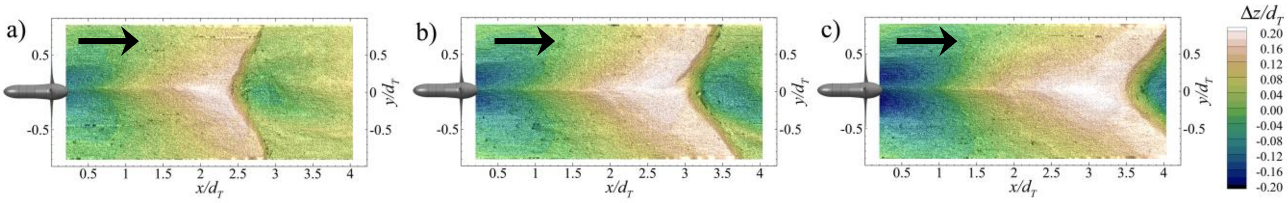

Figure 3: Time-resolved scour/deposition evolution downstream of a turbine. Figures refer to a) 30, b) 60 and c) 90 minutes into the experiment. Rotor diameter, d_T = 0.5m. Similar data exist for every 73s over the duration of the experiment (Hill et al 2014).

Small-scale experiments investigated cases with a single turbine, two turbines with variable aligned spacing and a seven turbine array (Fig. 4) installed above fixed bed channels, erodible channel with no active bedload transport and active bedload transport with either ripples or dunes migrating past the turbine(s) locations. Continuous bathymetric measurements indicate local turbine induced scour in erodible channels. Initial analysis indicates far-field effects of turbine(s) have minimal impacts on sediment transport.

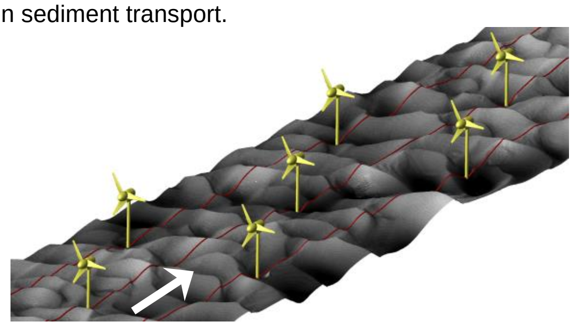

Figure 4: (Left): Topography from small-scale experiments with array of 7 turbines (d_T = 0.15m, S_x = 7d_T, S_y = 3.5d_T). Red lines indicate streamwise transects where continuous bathymetry measurements were collected.

Natural channels will likely exhibit complex, asymmetric geometries with a variety of stationary and/or mobile features introducing a range of coherent turbulent eddy scales into the flow. With the small-scale turbine installed in the OSL asymmetric meandering channel, the presence of the turbine locally redistributes transporting sediment. Fig. 5 shows a local lowering of the mean bed elevation compared to the baseline conditions without a turbine, a relative increase in mean bed elevation on the inner bank and a level plateau immediately downstream of the turbine location.

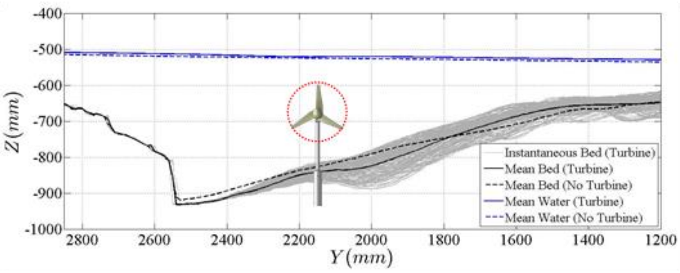

Figure 5: Comparison between mean bed surface elevations in the OSL asymmetric meandering channel with (solid line) and without (dashed lines) a hydrokinetic turbine model. Rotor diameter, d_T = 0.15m. Light gray lines show instantaneous bed profiles.

4. FUTURE APPLICATIONS

Results from these studies provide useful insight for the next generation of hydrokinetic devices. Opportunities for developing advanced controls demonstrate potential for improving device resilience in the turbulent environments they will be installed in. With proper site characterization of turbulent flow and bathymetry, developers can incorporate turbine control strategies such as blade pitch control or rotor angular velocity control (i.e. torque control). The inclusion of such feed-forward type control strategies utilizing real-time monitoring sensor networks could prove to lower the cost of energy for MHK developers, making it more desirable to continue developing turbines towards utility scale projects.

5. CONCLUSIONS

Multi-scale experiments addressing the uncertainties surrounding interactions of MHK devices and the physical environment have been completed at SAFL facilities at the UMN. This test bed combining state-of-the-art experimental and computational facilities has provided an initial understanding of how turbines interact with the complex environments they will be installed in. Single turbine large-scale experiments and both single and multi-turbine array investigations completed at small-scale have provided key insights on how both stationary and mobile topography impacts device performance, and how turbines interact with erodible channels under both clear water and live bed sediment transport regimes. Channel roughness (i.e. ripples, dunes, or stationary features) introduce large-scale eddies that impact turbine performance and wake characteristics. The spacing between the turbine and these obstacles can either positively or negatively influence its performance. Locally enhanced scour was observed immediately downstream of the turbine location (up to 1-2d_T) while far-field effects on sediment transport seem to be minimal. Turbines placed in meandering asymmetric channels exhibit a similar local impact on sediment transport. Ongoing analysis is investigating the effects that helical flow patterns have on turbine performance and wake characteristics. Results for these experiments have begun addressing the uncertainty surrounding the interactions between turbines and the physical environment and have provided some key insights that can potentially inform MHK device developers for incorporating advanced control strategies into future generations of turbines to optimize individual turbine and multi-turbine array performance.

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